TROLEX

How real-time data could be the beginning of the end for occupational silicosis.

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July 2022.

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Executive summary

Silicosis is now the most common occupational lung disease in the world, and silica dust has been described as ‘the new asbestos’ due to the extreme threat it poses to human health.

In fact, the potential for harm is even worse than that when you consider that asbestos is simply one of many different silica compounds and that silica is the most proliferate mineral on earth. It is present in bricks, sand, stone, concrete, glass, cement and many other construction and building materials.

This is one of the main reasons that 99% of deaths in occupational settings are caused by the inhalation of dangerous particulates – with the other significant factor in this statistic being the extreme difficulty in monitoring in real-time for these killer particulates.

It has never been possible to reliably detect and distinguish silica dust in real time in the real-world settings in which workers are exposed to it – until now.

The white paper looks at the background of silica exposure, the current methodologies employed to monitor it and the new technological advancement that has led to the development of a field-ready product that can achieve what has been described as "The Holy Grail of health and safety technology" for the first time in history.

Silica dust or respirable crystaline silica (RCS) is extremely harmful to human health even in minute (and often invisible) quantities due to its physical and biological properties.

It affects around 50,000,000 workers in a wide variety of industries all around the world and prolonged exposure leads to silicosis as well as a wide range of other diseases, most of which are untreatable and often lead to long-term disability and/or death.

Legislated limits of exposure have been tightening up in most major economies as the harm being caused becomes known, but reductions in limits and the implementation of these limits have been hampered by the lack of real-time accurate and reliable monitoring capability.

Current dust monitoring methodologies which can be broadly categorised as gravimetric sampling or Optical technologies are not capable of delivering real time dust monitoring in a reliable and practicable way and neither of them are even close to being able to deliver real-time silica monitoring.

Gravimetric sampling has a very wide range of negative usage factors and is highly inaccurate, but its fundamental weakness is in delivering results after laboratory analysis which can take days or even weeks.

Optical technologies are unreliable in real-world settings and incapable of reliably distinguishing silica dust from other particulates, meaning there is no way to implement effective real-time monitoring of silica dust.

Optical Refraction Technology is an entirely new development in the particulates field that has led to the creation of a new field-ready product (Air XS from Trolex) that can reliably detect and report on RCS exposure in real-time in the real-world settings in which it is needed – construction sites, mines, tunnels, quarries and process industries.

It works by analysing the size, shape and refractive qualities of particulates and is capable of distinguishing silica particles of all types from less harmful dusts and tracking changing levels of these particulates over time.

It is deployed in open-path sensing hardware that allows it to be used by workers with no specialist knowledge, to be maintained quickly and easily in around two minutes a month, and which requires no specialist skills to set up or to access the required data.

This technology has the potential to change the way industry, governments, businesses and workers themselves respond to the threat of RCS exposure in the workplace, and as such, it can be the beginning of the end for occupational silicosis. Not only does it improve health and safety outcomes for frontline workers, but it also reduces costs for businesses whilst giving them back control over their working environment.

Perhaps most importantly of all, it gives legislative bodies the tool they need to create and implement workplace exposure limits (WELs) that genuinely protect workers from harm, at a cost industry can bear, ending decades of debate over what the limits should be and how practicable it is for industry to meet them.

Introduction

Silicosis is not a new disease, having been identified and described at least as far back as Ancient Egypt and Greece[1], where stonecutters, builders and masons all exhibited obvious signs of the disease. It once again became a focus of attention during the industrial revolution, as processes and tools that created large amounts of fine particulate matter, that can penetrate deep into the lungs, were introduced to many workplaces. A 1939 study of men who had worked in the slate mines of North Wales found that 62% of the workers had silicosis in one of its three main stages[2].

In more recent times silicosis has been over-shadowed by asbestosis, which became the focus of attention in many Western countries in the 1970s and 80s. Whilst the two diseases have some differences in the pathology process, they also share many similarities – often long latency periods, persistent inflammatory responses in the body, and the fact that both are progressive and untreatable. This is perhaps not surprising when it is considered that asbestos is in fact just one of the many hundreds of different silica compounds.

This focus on asbestos, whilst necessary and effective in controlling and reducing the harm caused may have had a knock-on negative effect on the awareness of and uptake of preventative measures associated with silica and silicosis.

Silica is the most proliferate mineral on earth and therefore the potential for exposure is considerable. By some measures silicosis is now the most common occupational lung disease in the world[4] but the picture is not clear as it is not screened for in many countries and is not a notifiable disease in many others. Morbidity rates could therefore be considerably higher than official statistics suggest and many deaths attributed to other lung diseases might have been caused in part at least to exposure to silica dust.

Another complicating factor is the difficulty in monitoring for and distinguishing respirable crystalline silica (RCS) from other dusts in occupational settings. Whilst the presence of RCS might be obvious in large quantities where visual identification is possible and where a known process creates a known particulate mix, RCS retains its deadly qualities in quantities far below the ability of the human eye to detect,

[1] Nosilex, History of Silicosis.
[2] Davis. T, Silicosis in slate quarry miners, 1939.
[3] Mossman. Brooke T and Andrew Churg, Mechanisms in the Pathogenesis of Asbestosis and Silicosis, 1997.
[4] Dotic. S and Nola. M, The respiratory system.

and evidence suggests that the smaller non-visible particles penetrate more deeply into the lungs and cause the greatest amount of damage. This combination of factors makes RCS a critical threat not only to front-line workers, but also support or office-based staff, contractors, and neighbours of facilities with RCS generating processes, and means that whatever control and elimination methods are put in place, some doubt will always persist as to whether a workplace is in fact free of RCS or within legally prescribed limits.

The lack of accurate, real-time information has also meant that the imposition of enforceable regulatory limits on exposure to RCS has been slow. The HSE in the UK has cited this 'technology gap' as one of the main reasons for not moving to reduce the exposure limit telling Hazards Magazine in 2014 that considerations of lowering the limit have "focused on the ability to reliably measure below this limit in the workplace. Although under controlled conditions it is technically possible to measure below 0.1 mg/m^3 results of work undertaken by the Health and Safety Laboratory [HSL] have shown that this is not currently practical within a workplace setting."

Whilst this has not prevented other territories from reducing exposure limits below those of the UK, debate has raged on about the practicalities and costs of monitoring and responding to these lower limits. A February 2014 statement on the proposed OSHA standard from the American Chemistry Council's Crystalline Silica Panel, for example, noted "it is unclear" how the proposed standard "could be enforced given that serious questions remain about the ability of laboratories to measure silica exposures accurately and reliably at such low concentrations."[5]

Current monitoring technologies do give some indication of RCS levels in occupational settings but in reality these are frequently inaccurate, are often unable to distinguish RCS from other dust components or from less harmful amorphous silica particles, and do not deliver results in real time. Methodologies are often complex, time-consuming and specialised in nature, and deploy large, heavy, fragile and impractical hardware. Even the standard method of reporting based on mass (mg/m^3) is questionable in its efficacy as this is only one of a number of factors that determine how dangerous particulate inhalation is. Reporting mass values for smaller particles, 1 µm or smaller, for example, can often lead to variable results due to overall size, count

[5] **Hazards Magazine, 2014.**

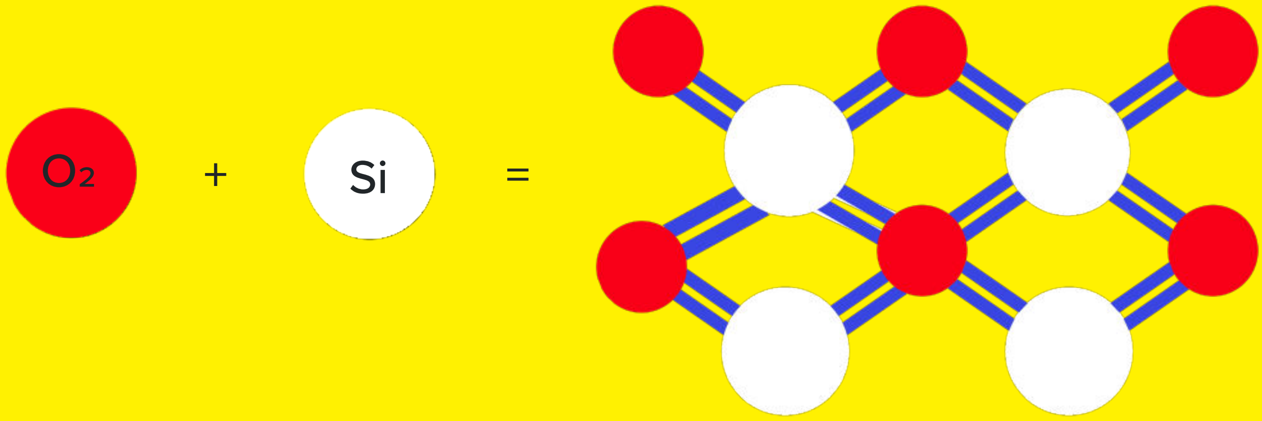
and mass at such a scale. In typical situations, a far greater proportion of small particles will need to be present to determine a reliable mass measurement in comparison to larger particles.

Real-time, accurate monitoring of RCS levels in occupational settings, capable of differentiating silica from other dust components and delivering results closely aligned to the harm-causing profile of the particulates would fundamentally change the above picture. The ability to enforce exposure limits that complied with research on non-deadly exposure levels, and to do so without burdening industry with high costs or resource requirements would also change the nature of the debate on how to move forward in dealing with the threat of silicosis in occupational settings. It would mean that industry and regulators could work together to implement a solution that reduced costs, reduced harm and delivered certainty for all those involved.

Recent technological advancements have made these outcomes a realistic possibility, and with them comes the potential to end occupational silicosis for good.

This paper looks further into this technological advancement and how it might impact the way in which silica dust is thought about, monitored, controlled, eliminated and legislated for.

Background



Silicon dioxide (SiO_2)

The chemistry of silica

Silica is another name for silicon dioxide (SiO_2) which is made up of two of the earth's most abundant elements: silicon (Si) and oxygen (O_2). It is a group IV metal oxide that occurs in nature. All silica forms are identical in chemical compisition but have different atom arrangements; silica compounds can be divided into two groups, crystalline (or c-silica) and amorphous silica (a-silica or non-crystalline silica).

c-Silica compounds have structures with regular repeating patterns of silicon and oxygen whilst a-Silica chemical structures are more randomly arrayed. All forms of silica are odourless solids composed of silicon and oxygen atoms and in particulate form Silica compounds become suspended in air and form non-explosive dusts.

Therefore, silica can either be crystalline or amorphous and it is the crystalline version in breathable particulate form (RCS) that we are most interested in when considering the threat to workers in occupational settings.

Crystalline silica exists in seven different forms. Four of which are very rare with the three most common being quartz, cristobalite and tridymite. Quartz comes in two different polymorphs, α-quartz and β-quartz. The most common is α-quartz and is found in large quantities in rocks and soils worldwide. Quartz, cristobalite and some forms of tridymite are inherently piezoelectric. This happens on direct application of pressure to the crystal. It is theorised that these piezoelectric characteristics may play a role in the pathophysiology of silica-related illnesses, though this is not proven. The mechanism of action involves generation of oxygen free radicals on the cleaved surfaces of silica molecules.

Why is it so harmful?

Whilst the mechanism of harm is not fully understood it is theorised that the properties of silica that influence inflammation are related to the silanol (SiOH) distribution in the silica particles.

Both amorphous and crystalline silica cause lung damage, however, internal silanols are typical in amorphous silicas, whilst surface silanols are dominant in crystalline silica. It is these surface properties of the crystalline particles that are critical in conferring the biological properties that cause harm. This challenges the common school of thought which attributes damaging biological properties simply to its physical shape or sharp edges, although this may be a significant factor too. Silanols present on the surface of silica particles are capable of forming hydrogen bonds with oxygen and nitrogen groups found in biological cell membranes.

CRYSTALLINE SILICA DUST.

Surface properties of crystalline particles are critical in conferring the biological properties that cause harm.

Reactive oxygen species (ROS) are key in normal functions of cells, including defence against unwanted intruders. However, if too many are created, their reactivity leads to tissue damage. When a silica particle enters the lung, it can immediately react with the lung environment to generate ROS. The generated ROS in turn reacts with and damages the epithelial cells of the lungs. But it gets worse. A macrophage consumes and attempts to digest the particle with more ROS. Eventually the cell realises that it cannot digest the particle, and self-destructs. Self-destruction is meant to avoid further complication when a cell's processes fail. However, this releases all the built up ROS and the silica particles back into the lung environment, and the process repeats itself.

Freshly cut and smaller silica material is able to create ROS more readily and is potentially more toxic than larger and/or aged material. The respirable particulate fraction (0.2 - 10 µm aerodynamic diameter) is that fraction of inhaled airborne particles that can penetrate beyond the terminal bronchioles into the gas-exchange region of the lungs. The National Institute for Occupational Safety and Health (NIOSH) studied different reactions of lung tissue to different size silica particles ultrafine (0.3 µm) vs coarse (4.1 µm). Conclusions from the study showed that there is significantly more reactivity from smaller particles compared to larger particles in macrophage activation.

Silicosis differs from asbestosis in that whilst asbestosis is a lower-lung predominant disease, silicosis is upper-lobe predominant. Silicosis can often increase the risk of tuberculosis (tuberculosis is also upper-lobe predominant) and other respiratory and lung infections. Unlike other respiratory illnesses, though, there may be extensive damage to the lungs, typically fibrosis, cancer and respiratory failure before any clear symptoms appear.

In the UK and many other territories, the primary care investigations only begin on first presentation. This is far too late for any realistic treatment options and as the damage cannot be reversed, there are few treatment options available at this stage. In addition there are no guidelines or recommendations for practitioners to maintain records of those who have previously worked in an RCS environment.

WHAT'S THE DIFFERENCE?

Asbestosis is predominantly a lower-lung disease whereas silicosis is predominant in the upper-lobe.

Silicosis also causes extensive damage before any symtoms may occur.

Diagnosis is variable and at present is usually obtained by chest x-ray. However, studies have suggested that chest x-rays are not sensitive enough as the primary means of diagnosis in the early stages. There are numerous studies showing that chest x-rays are not as sensitive as CT scans and could result in individuals having to return for a follow-up scan, which could delay diagnosis. Some studies have stated that the use of x-rays to investigate suspected lung cancer may even be harmful. Very early cancers can be missed in x-rays, giving false reassurance to patients who typically will wait longer before presenting again following the initial results.

The Lung Cancer Clinical Expert Group (CEG) in the UK strongly advises a “CT first” approach and the evidence overwhelmingly endorses this.

What are the risks associated with exposure to RCS?

Exposure of workers to RCS is intensity, frequency of contact and duration dependent. This obviously differs from one workplace to the other but essentially the risk of developing silicosis is closely linked to accumulated exposure to RCS during an individual’s working life. It is a preventable but irreversible occupational lung disease. *Table 1* shows different types of stones and their respective percentage amounts of silica. The higher the amount of silica, the riskier it becomes. No amount of exposure to silica dust is safe and the main pathogenic effect of the sustained inhalation of silica is the development of silicosis. It is characterised by chronic inflammation and scarring in the upper lobes of the lungs. Radiologic findings using chest x-ray confirm well-defined opacities located in the upper lobe and posterior portion of the lung. High-resolution computed tomography (HRCT) further confirms confluence of nodules predominantly in the upper lobes of the lungs.

Silicosis can be classified based on the quantity inhaled, time course, and length of exposure. The three different types of silicosis are chronic, accelerated and acute. Chronic simple silicosis is the most common form occurring after 15 to 20 years of moderate to low exposures to RCS. The accelerated form occurs after five to 10 years of high exposures to RCS, and acute silicosis or silicoproteinosis, occurs after a few months or as long as five years following exposures to extremely high concentration of RCS. Acute silicosis is the most severe form of silicosis.

Types of natural stone or other mineral-based materials	Crystalline silica content (% w/w)
Stone, gritstone, quartzite	Above 70%
Mortar, concrete	25 - 70%
Shale	40 - 60%
China stone	Up to 50%
Granite	20 - 45% (typically 30%)
Slate	Up to 20 - 40%
Ironstone	Up to 15%
Basalt, dolerite	Up to 5%
Limestone, chalk	Up to 5% (typically less than 2%)
Marble	Up to 5% (but may contain veins of crystalline silica so the overall contact may be a lot higher

Table 1: Typical silica concentrations in different types of stone.

RCS is a carcinogenic silent killer. Inhalation of RCS does not only result in silicosis but it can also lead to and contribute to a very wide range of other serious health effects in the lungs such as chronic obstructive pulmonary disease (COPD), bronchitis, tuberculosis and lung cancer as well as non-respiratory diseases such as kidney disease, skin cancer and diabetes. In addition to the obvious health risks to individuals there are several other 'risks' of RCS in the workplace such as the influence it may have on workers decision to continue work or leave work permanently.

The after effects of RCS exposure and diagnosis of workers potentially leads to lawsuits, compensation claims, fines, and the breakdown of the companies public image which results in loss of revenue.

Again, in this area, silica has until recently played second fiddle to asbestos which has seen a slew of high profile lawsuits, the biggest of which was against Johnson and Johnson and which led to damages estimated at $3.5 billion, with more actions in the pipeline. More recently, in the UK, the BBC has been forced to set aside £350 million in order to compensate the victims of mesothelioma caused by asbestos present in their recording studios, and this is likely to be just the tip of the iceberg in terms of forthcoming claims.

Silicosis lawsuits, however, are beginning to gain greater prominence and have a greater financial impact on businesses, driven by the increasing awareness of the danger posed and improving diagnostic capabilities. In the US, a former sandblaster won a $7.6 million pay out against the Mississippi Valley Silica Company, and in South Africa miners took 30 mining companies to court and won a $400 million settlement for potentially tens of thousands of individuals affected by silicosis. As with asbestos-related claims these are likely to be the forerunners to many more actions now that clear and obvious causality has been established.

Such legal cases can also cause a major shift in workforce preferences and patterns for fear of contracting lung diseases and from reputational damage to the industries and businesses involved. This increases shortages in the labour force and drives up employment costs.

The classification of RCS as carcinogenic for humans has drawn greater attention to occupational and non-occupational exposure in recent years. However the rate of resurgence of silicosis in many industries, driven by large infrastructure projects, construction booms and increased mechanisation has also led to a realisation that responses to the presence of RCS need to be radically improved if the world is to avoid a 'new asbestos' crisis or worse, and if businesses are to avoid potentially existential threats from lawsuits and governmental scrutiny.

What are the risks associated with exposure to RCS?

The realities of RCS exposure and incidences of silicosis can be seen through a comprehensive collection of statistics, cases, and scenarios from around the world. An estimated 600,000 workers are exposed to RCS in the UK, and the consequences of silicosis are estimated to cost employers in the construction industry at least £1 million per month with this figure likely to rise exponentially as awareness of the widespread harm being caused increases. In 2020, the Health and Safety Executive (HSE) reported that 12,000 people died from lung diseases estimated to be linked to past work exposure to particulates in a range of sectors.

A British Occupational Hygiene Society (BOHS) study of underground tunnel construction workers in London showed that the personal eight-hour time weighted average (TWA) shift exposure to RCS on a back-up sprayer was 0.24 mg/m^3 (more than two times the HSE workplace exposure limit (WEL)) during sprayed concrete lining activities in the tunnel. In HSE's document, EH40 *"Workplace exposure limits"* the WEL for RCS and amorphous silica are 0.1 mg/m^3 and 6 mg/m^3, respectively. RCS is a Group I carcinogen, whereas amorphous silica remains in Group III.

A NIOSH report from Cincinnati in the USA showed that between 1990 through to 1999 silicosis was one of the most frequent conditions recorded on death certificates and more than one-third of the deceased with silicosis had worked in construction or mining. More recently in the US a 2022 NIOSH study found a clear link between exposure to silica and workers with black lung disease in the mining industry, the incidences of which have been on the increase since the 1990s. In South Africa, contemporary silicosis and active tuberculosis prevalence rates in gold miners coming to autopsy were concerningly high at 29.4% and 16.5%, respectively, in 2017.

Workers continue to pay the price almost a century after the Hawk's Nest Tunnel disaster in the US, in which hundreds of mainly young minority-ethnic workers developed acute and accelerated silicosis while drilling a tunnel through the pure quartz (more than 70% silica present from *Table 1*) of Gauley Mountain, West Virginia, to bring water to a power station.

Over 500,000 Australians are exposed to RCS in the workplace annually. Within Australia, chronic silicosis was long thought to be well-controlled. Its recent re-emergence within the tunnelling and manufactured stone industries, where 20% of workers have silicosis, hints at potentially a more widespread presence of undiagnosed occupational lung disease.

This has far reaching implications for workers, employers, compensation systems, and the public healthcare sector. A Greek investigative study of outdoor and underground construction workers concluded that underground workers with more than 15 years of exposure to RCS are 78% more likely to present chronic silicosis compared to workers engaged in outdoor activities.

In Turkey, a 6.2% mortality rate from silicosis in young individuals that worked in the garment sandblasting industry suggested overexposure and unsafe working conditions due to a lack of controls. As a result, sandblasting of garments was banned in Turkey in 2009. However, some jeans producers have reportedly moved their orders to other nations, with research suggesting that sandblasting is taking place in China, Bangladesh, India, Indonesia, Pakistan, Cambodia, Egypt, Jordan, Syria and Mexico.

Many cases of silicosis have resulted from artificial stone fabrication work and have been reported from Australia, Belgium, Israel, Italy, Spain, China, Canada and the United States. Given the toxicity of silica-laden artificial stone, researchers from The University of Illinois at Chicago School of Public Health suggest that if engineering controls cannot limit worker exposure to RCS, a ban on these stones must be in place in some states in Australia where one-in-five stonemasons have been found to have contracted silicosis. A 2009 to 2018 Spanish study conducted on artificial stone workers revealed that artificial stone silicosis rapidly progresses to progressive massive fibrosis even following exposure cessation. A significant percentage of patients experience a very rapid decrease in lung function.

It is estimated that the number of workers in Europe who have been exposed to silica is between 3 and 5 million, in China more than 28 million and 10 million in India. This exposure is responsible for at least 10,000 deaths per year worldwide, although there is likely to be a very significant underreporting in that figure as many countries do not require silicosis to be screened for – or monitored as standard – or to be specified on death certificates and the number takes no account of co-morbidities with other diseases.

If that was not bad enough the numbers of those exposed to silica dust may also be significantly under-reported as they often only include those front-line workers directly involved in the dust-creating process. Office workers, administration staff, site-contractors and individuals working nearby are also at risk, as was highlighted in 2021 by the case of a 34-year-old woman in Australia working in an administration building near to a quarry who contracted silicosis from dust inhalation, having worked there for just seven years.

Is there a general consensus of RCS exposure limits globally?

There is no general consensus to the RCS exposure limits across the world and the current regulations differ to a considerable extent. The highest values (0.10 - 0.15 mg/m^3) are allowed in Israel, United Kingdom and New Zealand. Australia recently lowered its RCS exposure limits to 0.05 mg/m^3 and is considering a further reduction to 0.025mg/m^3. In the US, The Occupational Safety and Health Administration (OSHA) value is 0.05 mg/m^3, which was also suggested by the Scientific Committee on Occupational Exposure Limits (SCOEL) in Europe. The Japanese Society of Occupational Health (JSOH) level is 0.03 mg/m^3. The lowest concentration of 0.025 mg/m^3 is established in Canada and Portugal. These differences indicate that it is difficult to define clear limits.

Concerns around the inability of current air monitoring equipment to measure rates of 0.025 mg/m^3 led to the interim

[6] 9news.com.au, February, 2021.

adoption of 0.05 mg/m3 in NSW, Australia, however this standard operates in a way that nevertheless recognises that illness, injury and death can occur at exposure rates more than 50% below that level. Since 2016, the American equivalent of the WES has included an action level above 0.025 mg/m^3 as it is known that workers exposed to levels of RCS, equivalent to 0.05 mg/m^3 for their working lifetimes (40 - 45 years) still have significant risk of developing chronic radiographic silicosis.

Most health organisations use the risks of silicosis and lung cancer in humans to define limits, and monitor lung function as an indicator of an individual with a potential issue. However, studies with active workers may lead to an underestimation as silicosis is found more frequently in retired individuals, with the disease having continued to develop and worsten post-employment.

Furthermore, it is notable that changes of lung functions are not necessarily characteristic for silicosis and therefore not a good indicator, at least in the early stages, of a developing disease process. When exposure limits are set on the basis of threshold levels for inflammation, the values are considerably lower than those for prevention of cancer and silicosis, making the challenge of recent advances in monitoring technology and concepts mean that it is now possible to measure RCS exposure in 'real time' potentially at levels that are at regulated quantities or even lower, providing the intriguing possibility of being able to prompt 'right now' decision making in industrial settings where silica is present, and giving regulators, industry and workers groups new tools to deploy. These technology advances raise objective conversations around global legislation of RCS, workplace health and safety (WHS) policies and regulation and labour practices.

Could real-time monitoring technology really contribute to policy changes?

Health and safety should be at the heart of all operations and processes and the goal in silica generating industries should initially be the elimination of fatalities, followed by a movement towards a goal of zero harm from these particulates. There are a number of ways that this can be achieved or contributed to including better awareness and education, stronger internal business policies and procedures, improved local or on-machine dust controls, better ventilation, suppression, extraction and containment systems, improving or changing dust generating processes, and more robust hierarchies of control. On the societal level, better regulation and standards combined with stronger oversight and enforcement, as well as policy changes and simplifications of legal processes can all contribute to improving the situation, as will improvements in health monitoring, screening and reporting related to the disease. However, nearly all of the above developments rely at least to some extent on the ability to provide better and more immediate particulate monitoring information, the pinnacle of which must be real-time particulate monitoring (RTPM) in the industrial environments in which the harm is being caused.

The International Council on Mining and Metals delivered a report in January 2022 entitled Considerations for the *Adoption of Real-Time Particulate Monitoring*, which states that "since RTPM measures quickly, it is an effective tool for identifying uncontrolled or unexpected critical releases of hazardous particulates, pinpointing specific activities within job tasks that have a high likelihood of exposure. It could also be used to improve and confirm Similar Exposure Groups (SEGs), and for validating the effectiveness of existing controls. Therefore, ICMM members believe that RTPM is a proactive and effective tool for preventing hazardous airborne particulate exposures, mitigating associated risks, and validating controls."

The ICMM report is one of the first serious attempts to engage with real-time monitoring as a foundation for building a serious zero-harm policy around particulate control. It recognises that to change policy through real-time technology there must be digital integration of real-time data with administrative controls and workplace design standards. This active support of real-time technology and data integration has the potential to improve industry best practices and drive towards policy changes that can have a real impact, but the report also highlights the limits of existing technologies in achieving this which, until very recently, have consigned it to the realms of an unrealistic ambition.

Similarly in the UK, *British Standard BS 6164:2019 Health and Safety in Tunnelling in the Construction Industry: Code of Practice*, came into effect end of October 2019. This *British Standard* is a full revision of the now-superseded *BS 6164:2011*. It paved the way for a construction industry that focuses on the continuous monitoring of dust; and real-time data is at the pinnacle of achieving this in different RCS generating workplaces. This move by the British Standards is highly significant and serves

as the first leap towards a real-time, data-driven workplace which relies on ‘right now’ information. The revisions performed in *BS 6164:2019* acknowledge workers health as a priority and the role that continuous dust monitoring plays in prevention of dust-related diseases.
As we approach the third year since its publication, the move towards real-time monitoring as a significant development of safety protocols around RCS in the tunnelling sector is yet to gather any real pace, largely because the technology available has not been able to fully support the ambition.

These developments demonstrate clearly that the understanding of the benefits of RTPM and the willingness to adopt the technologies into regulation is growing amongst industry and regulatory bodies. However, what both initiatives also demonstrate is that in order for RTPM and specifically real-time RCS monitoring to really inform workplace practices and ultimately change the regulatory landscape any new technology must offer high-speed data that is processed in real-time and which is capable of positively identifying and distinguishing silica content in dust mixtures in real world settings. In addition, it needs to be accessible remotely for enforcement, resource allocation, workplace safety and health and accountability where swift action is urgent. Finally, and critically, it must deliver all of this in a way that is both practicable and cost-effective for those using it so that industry, workers, regulators and governments can all get behind changes and developments to regulatory frameworks and the businesses practices associated with them.

Section 2 of this paper looks at currently deployed technologies and methodologies for particulate monitoring, the benefits and shortfalls associated with these different approaches, and specifically why they are currently not capable of providing cost-effective and practicable RTPM in challenging industrial settings or real-time RCS detection in most settings outside of a laboratory.

An overview of general dust monitoring technologies and techniques

Workplace related materials that are hazardous to health are often generated or present in the form of aerosol mixtures, which describes the suspension of particles in the air. Aerosols can be made up of wide range of particle diameters and types, including dusts, fibres, fumes or liquid droplets.

Occupational dust is typically measured using personal and/or area sampling techniques detailed below, and although a cross-section of devices have been developed to measure airborne particulates and aerosols over the years, the two primary methods that have established themselves for use in particulate exposure assessments whether personal or area related, can be broadly categorised as gravimetric sampling and optical measurement devices.

Area monitoring

Sampling particulates from and within the general working environment allows assessments to be made on changing dust saturation levels, peak particulate levels, identification of dust generation sources or leaks and the overall effectiveness of process controls or ventilation and containment practices employed.

Given the impact that environmental factors can have on airborne particulate levels and concentrations, the collection of multiple data sets from the general working environment can be an important part of informing effective dust control and response measures.

Personal exposure monitoring

Personal particulate samples are collected proximally to the breathing zone of a specific worker with the aim of representing the total fraction inhaled by that worker during a given shift.

Particulate sampling with gravimetric analysis is traditionally the most prevalent method for estimating personal hazardous particulate exposures and the method that most commonly meets regulatory compliance requirements, however in recent years personal samplers that use optical measurement have also become available for general dust monitoring.

Particle sizing and selection

Personal monitoring devices typically use size selective cyclones or impactors that act to limit particulates collected via deposition. This is with the main aim of correlating particle collection activities to a specific size range linked to inhalable, thoracic and respirable fractions as described in *ISO 77081* or *BS EN 481*.

- **Inhalable fraction**
  This approximates to the fraction of airborne material that enters the nose and mouth during breathing, and is therefore available for deposition anywhere in the respiratory tract.

- **Thoracic fraction**
  This is the fraction of inhaled airborne material penetrating beyond thelarynx.

- **Respirable fraction**
  This is the inhaled airborne material that penetrates to the lower gas exchange region of the lungs.

It is commonly recognised that larger particulates, or 'inhalable' particulates (≤ 100 µm) will collect in the upper respiratory system like the nares and upper throat where they may be cleared or digested. Medium-sized particulates in the size of ≤ 40 µm or 'thoracic particulates' can penetrate to the bronchi and bronchioles.

Smaller particulates (≤ 15 µm) or 'respirable particulates' can traverse through the turns of the nares and upper throat and make it to the deep lungs, where they can be lodged into the alveoli and thus damaging the cells in the gas exchange region.

The smallest particulates (≤ 0.5 µm) are the most complex because they behave more like gases than particulates, entering deep into the lungs where gas exchange occurs and potentially entering the blood stream, or exiting via exhaled breath. By understanding the aerodynamic diameter of airborne particulates, an estimate can be made of where they may pose the most risk when inhaled.

Exposure risks

Size and density alone are not enough to fully assess risk from exposure to airborne particulates. Understanding the risk of hazardous particulates in the workplace also involves characterising the 'what, when and how much' of worker exposure. Speciation involves identification of what individual types of dust within a mixture consist of, which helps to narrow, identify or clarify the list of potential health threats posed. With the ability to identify and quantify the species contained within aerosol compositions, comparison can be made to occupational exposure limits which in the UK are outlined in the *EH40*

Workplace Exposure Limits and the *Approved Code of Practice* on the COSHH Regulations. Every territory has its own version of these limits and regulations backed by government, industry and private bodies.

Monitoring technologies

Gravimetric sampling

Gravimetric sampling is the main technology used for the collection and analysis of silica dust and is typically the methodology referred to in regulations. At the time of its initial development and deployment into the workplace over half a century ago, gravimetric sampling was the only technology that was capable of detecting the presence of silica dust which explains its prevalence in regulatory environments and why exposure to silica dust is most often described in mg/m^3, the measurement obtained through gravimetric sampling.

Gravimetric sampling typically relies on the initial function of drawing a sample of contaminated air through a size selective filter, cyclone or impactor plate, after which the remaining solid is collected on a pre-weighed substrate of filter material. The collected sample is then further analysed using a lab based optical method, to determine the overall composition of the sample and when combined with the airflow and collection time-base, can be used to evaluate personal or area exposure measurements.

It is most often deployed as a Pumped Personal Sampler where the device typically takes the format of a personally positioned sampling head, relative to the breathing zone, containing a size selective filter and particulate collection area and a pumped airflow source to draw particulates onto a target material trap. Pumped sampling devices are available to specifically target a fixed particle size, with others designed to sample multiple size fractions within a single sample, known as multi-fraction. Pumped personal samplers normally rely on a waist mounted pump and battery pack that supply continuous power and airflow to the system.

Consideration of the type of pumped sampler that should be used depends on several factors including the size fraction of interest and aerosol concentrations. Typically, mass measurements are collected for long-term sampling (greater than four hours) using a target flow rate of 2.1 l/min, designed to reflect the rate at which a human would inhale during normal respiration. In instances where aerosol concentrations reach variable or high levels, or there are significant levels of large particles present, it is commonly assumed that the sampler may provide unrepresentative exposure measurements[7].

[7] HSE, General methods for sampling and gravimetric analysis of respirable, thoracic and inhalable aerosols MDHS14 (hse.gov.uk).

Commercially available samplers and references to published reports on their performance are given in *PD CEN/TR 15230*[8].

Laboratory-based optical measurement technologies are used to analyse samples collected through gravimetric sampling devices to provide the final outcome from this methodology. Whilst they are generally more stable and accurate than field-based optical measuring devices obviously they have no capability for use in hazardous industrial settings. These optical measurement technologies include:

- **XRD (x-ray diffraction)**
  X-Ray diffraction is a method of crystallographic structure analysis, determined through the measurement of an x-rays' intensity and scattered angles that leave a prepared sample material. During the analysis method, diffraction patterns and peaks are observed and used in the identification of materials within the collected sample.

- **Fourier transform infrared spectroscopy (FTIR)**
  FTIR functions are based on the changes in absorbance of infrared radiation as it passes through a particulate or material sample. The frequency that molecules absorb is indicative of the structure as specific bonds are vibrated. Differences in the absorption or transmission spectra can be used to identify target material types within sample mixtures. FTIR can now be used in the work place to measure RCS from gravimetric samples, but this must be completed still at end of shift so only reduces the delay in the results without providing real-time measurements.

- **Raman spectroscopy**
  Raman spectroscopy is a molecular identification technique that also uses the principle of the interaction of light with a sample to identify the characteristics of a material. Ramen is designed to capture the vibrational signatures from a materials molecular structure, giving an indication of material types or variances but involves a scattering process unlike FTIR. Technical complexity had made this technique less common to the similar FTIR but recent advances in instrumentation are making this more wide spread.

In-field optical measurement devices are sometimes combined with laboratory analysis or even gravimetric sampling to attempt to monitor for silica in real time.

[8] **European Standards, PD CEN/TR 15230: 2005 Workplace atmospheres. Guidance for sampling of inhalable, thoracic and respirable aerosol fractions, (en-standard.eu).**

Typically the analysis of a sample taken from the site using gravimetric sampling will yield a silica percentage, which is applied to an overall generic dust count in real-time using optical measuring devices, with the silica content inferred from the combination. Alternatively known inaccuracies in silica dust detection ascertained through comparing on-site detection with laboratory analysis will be adjusted using a 'correction factor' in an attempt to align the optical measurement device, giving an inferred real-time silica reading.

Optical measurement devices and alternatives to gravimetric sampling.

More recent technological developments for real-time dust measurement have involved the use of optical measurement devices, and when combined with dust sampling or supporting analysis of silica particulates these technologies can be used to attempt to detect silica dust in real time.

In-field optical measurement technologies can be generally categorised as follows:

- **Optical particle counters**
  Optical particle counters use the principle of light extinction or light-scattering to count and sort particles by differed size or mass. A laser beam is typically used to illuminate a specific region of airflow, through which sample particles are directed. As each particle passes through the beam, light is absorbed and reflected, with a detector being used to measure the corresponding intensity. Light-scattering methods account for the collection of light that is scattered indirectly onto the detector, whereas light extinction accounts for the shadow measured when a particle breaks the beam directly illuminating the photodiode detector. Light-scatter methods are favoured for smaller particles (≤ 1 µm) due to the limit of detection using light extinction principles but can also measure particles of larger sizes.

- **Nephelometers**
  A nephelometer provides information on suspended particulates and density as a result of the incident light being reflected onto a photodetector from the passing particles. The resulting reflected light is a direct result of the particles properties, such as shape, density, colour and reflectivity.

- **Beta attenuation monitor**
  The principle of beta attenuation instruments is focused around the energy that is absorbed from beta radiation particles as they pass through the sampled material, which has been collected on a filter source. A baseline beta count through the filter alone must be established prior to particulate sampling, which is generated from a radioactive source. Typically, a maximum four PM measurement can be collected per hour.

- **Micro balance instrumentation**
  Micro balance instrumentation uses direct collection and mass measurement analysis by drawing the collected particulate sample through a filter at a constant flow rate whilst continuously weighing the filter. The information collected is used to calculate the mass concentration of the passing particulate matter. Due to the highly sensitive weighing balance used, this technology is not best suited to industrial applications.

- **Dust indicators**
  In some cases, a dust lamp is used as a method to highlight fine dust that is not visible under normal operating light levels. A powerful beam of light within the lamp helps to pinpoint the active source and movement of the small airborne particles. Whilst the method can indicate the presence of dust within working environments, it excludes any specific information about the aerosol such as size, speciation and concentration levels.

  Further information on using dust lamps and performance is available in *The dust lamp MDHS82*.

Whilst both gravimetric and optical methods have some use in providing indicative real-time measures, even where they are deployed to attempt real-time detection they can only be applied in conditions where processes create stable RCS content and concentrations, and where the processes themselves are unchanging and have a very low risk of process related events that might cause higher or lower levels of RCS to be released. Both methodologies are complex and resource intensive as well as presenting serious performance issues around accuracy and stability, and as such, neither present a viable route to effective real-time monitoring. In the majority of industrial applications where silica dust levels will not be absolutely stable, these methodologies can actually present a risk to workers exposed to RCS by providing inaccurate or unreliable information.

What are the current limitations of technologies available for silica detection?

As discussed above the gravimetric sampling method relies on the initial collection of particle samples using a pre-filtered or cyclone selective pumped sampling system, before analysing the sample in laboratory conditions using XRD, FTIR or Raman instrumentation.

Validity of the collected aerosol sample can be questionable due to the various factors that can influence the resulting dust deposit and the analysis result, which include:

- projectile particles
- large particles outside of the target particle range;
- the amount of particulate matter collected;
- oil or liquid splashes within the sampler;
- temperature, humidity and pressure effects;
- units require stable operating conditions which on a personal
- transportation losses;
- and handling error[9].

In addition to these issues with the sample collection process, the quality of the result may be further compromised due to the inherent inaccuracy of the laboratory analysis that follows. XRD analysis for example may typically yield results accurate to ± 18% with even this figure representing a 'best-case' scenario as accuracy levels can be further compromised if samples are incomplete, or contain non-standard RCS material, or if the particle size profile is untypical. It is considered therefore that gravimetric sampling provides at best only an indicative measure of silica exposure in a workplace.

Of course, the fundamental limitation of gravimetric sampling as a silica detection methodology is in the requirement for post-shift laboratory analysis itself. Results are obtained days or even weeks after the monitoring takes place rendering the methodology useless as a safety warning device. The recent introduction of on-site laboratory-style testing of samples has made it possible to obtain results a few hours after collection but this has resulted in further levels of inaccuracy, as staff are often not as proficient in the measurement as dedicated test houses, and it still does not provide real-time information to businesses.

There are several other limitations, complications and problematic aspects that apply to gravimetric and light-scattering technologies which create further challenges and must be carefully considered when deploying best practice monitoring methods within a working environment. These include:

- size, shape and weight of instruments;
- inability to be deployed in the field in challenging locations;
- the need to weigh filters and samples;
- changing out dust size selectors;
- need for uniformity of flow through apparatus;
- only offer mean dust concentration for time used;
- accuracy dependent on scale weighting the collected dust;
- calibration is dust location dependent;
- inability to recognise or distinguish crystalline silica types;
- reliance on vacuum system to collect and deposit dust;
- and disturbed by wavelength and scattering properties of silica.

Every technology currently deployed demonstrates some combination of these failings, often making the process complex, time-consuming, and requiring specialist skills to deliver any kind of meaningful result. As a result, the policy in businesses with known RCS exposure risks has been to revert to the use of specialist companies or individuals to conduct lengthy and expensive surveys on a regular basis, using the equipment to provide outline or inferred information to reference when decisions on engineering and HR control policies are created.

[9] HSE, General methods for sampling and gravimetric analysis of respirable, thoracic and inhalable aerosols MDHS14, (hse.gov.uk).

Sampling error, processing and data latency.

The overall effectiveness of sampling using current methods can be influenced by the uncertain nature of workplace aerosol concentrations[10]. As aerosols are often non-uniform in concentration, the position of the sampling device plays a significant part in the collection of a representative exposure sample as both height and distance from the source will affect the results.

Some sampling devices remove larger particles through the implementation of an impactor, which allows the smaller, respirable materials to be collected independently. Care, however, must be taken not to overload the sampling device, as it is common for efficiency of the impactor to reduce leading to the inclusion of large particles within the respirable sample which contributes to over sampling[11].

In most cases, cautious handling of the loaded sampler is required as additional material collected within the sampler can be deposited onto the filter media. The contamination of the filter can contribute to sampling errors.

Devices that use pre-weighed filter cassettes must be considered for weight variations or gains due to environmental moisture absorbance during use. With the mass of the collected aerosol sample being many times less than that of the collection substrate, the post weighing process measures the differential between the two, with the result giving a typical estimation of hazardous material which can be biased due to filter weight changes[12].

Filter based collection sampling methods are typically conducted over several hours with the aim of collecting a representative exposure sample size and to ensure there is sufficient mass to accurately measure. As discussed above, when combined with the additional post processing and analysis time frame, the resulting measurement can take days or even weeks to obtain. Since conditions present at the time of sampling may have changed, this time lag can delay the implementation of timely interventions to improve worker protections and can complicate and compromise the validation of control effectiveness and in particular any short periods of high RCS levels are averaged out and so processes of high risk are not identified.

[10] ISO 15767:2009 Workplace atmospheres — Controlling and characterizing uncertainty in weighing collected aerosols.
[11] HSE, General methods for sampling and gravimetric analysis of respirable, thoracic and inhalable aerosols MDHS14, (hse.gov.uk).
[12] ISO 15767:2009 Workplace atmospheres — Controlling and characterizing uncertainty in weighing collected aerosols.

In summary then, some of the main critical performance issues related to existing methods include:

- no real-time output;
- latency time between sample collection and results;
- inability to identify specific tasks or high exposure activities;
- user or environmental influence on inaccuracy and variability;
- minimum operating time periods;
- specialised equipment set-up, training and data interpretation;
- high levels of operator bias;
- rigorous and lengthy calibration process;
- fluctuating analytical sensitivity;
- and requires use of complex sampling apparatus.

To assist with the efficacy of a hierarchy of controls in relation to RCS dust and achieve its effective implementation, quicker interventions are required – ones that also provide accurate and stable results, are cost-effective and cost-sensitive, are robust enough to operate effectively hazardous industrial locations and which do not require high levels of specialist skills to carry out. As we will see in the next section recent advancements in real-time technology have made this a realistic outcome.

Technological developments creating a path to effective real-time silica dust monitoring

While particulate size selective sampling techniques are still used in many cases involving regulatory compliance, the future has to be the standardisation of real-time silica detection which would provide highly significant advantages for assessing hazardous exposures to workers where timely data generation and collection enables the assessment and implementation of instantaneous worker protections and control systems.

The basis of the technological advancement that is facilitating the leap forwards is the deployment of Open-Path Optical Refraction Technology (OP-ORT) alongside advanced Optical Particle Counting (OPC) allowing for an analysis of RCS particulates across a number of different parameters, generating responses unique to silica. The optical refraction technology detection method is designed based on the principle of measuring the photo radiation that propagates through certain particles when exposed to a specific light source. Through the application and detection of a certain set of optical parameters, changes in the passing signal allow for the mapping of crystalline silica particles against non-crystalline materials. In addition, the technology acts to prohibit signals from other particle types from entering into the detection region using a series of advanced optical components.

Through the continuous illumination of passing particles at a specifically tuned interaction point, each particle is subject to a controlled radiation beam that allows for the scattering, absorption and refraction to take place. Changes in the combination and detection of events help identify a range of properties that relate to the composition of the particle as it passes through the source beam. In addition, the specific mechanical position of detection elements relative to the particle axis is considered and provides an additional level of information regarding particle shape and size.

Using this method allows for a high number of particle interactions to take place every second, which supports the collection of large sets of information that are processed in real-time to give an indication of changing silica levels as particle concentration changes over a period of time.

Advancements in optical sensor technology mean that every particulate passing through the sensing region can be monitored and differentiated, and creates the ability to measure optical path changes and phase differences from the interaction of a particle with a series of specialist optical components. Size, shape and a series of crystalline qualities can also be analysed in real-time, triggering a triple-voting system that positively identifies silica particulates. Similar to complex lab-based equipment, a signature response or fingerprint is identified from the changes in material composition which allows for the positive identification of crystalline silica particles.

By combining this information with high speed data processing performance, instantaneous in-field results allow the technology to provide information in real-time as a field deployable monitoring system.

This new OP-ORT/OPC technology is capable of differentiating silica particles in dust mixtures and can track changing silica concentrations over time. The resulting detection information is delivered as a total particle count which when combined with the volume of air for the time period it provides the exposure amount in mg/m^3 for any given environment.

Trolex, a private UK company has led the development of the technology in its own bespoke laser-lab, carrying out over 12,000 hours of testing on various technology options and on a number of prototypes leading to a field-ready product. In order to support the real-time and in-field detection of silica specific particulate, a ground-up open-path optical sensor had to be designed to combine the following optomechanical and material analysis properties:

- dynamic particle interaction chamber;
- particle sheath control;
- photon interaction region;
- phase induced light-scattering;
- light polarisation;
- measurement of resulting differences in signature responses;
- and crystal axis index difference.

Removing the requirement of complex and bias prone particle collection methods, such as pre-weighed filters and size selective sampling heads, the new open-path technology has been designed to support a methodology that will measure harmful particulates from the full range of workplace aerosol sizes whilst providing additional useful information on hazardous sizes, changing concentrations and overall particle densities.

In conjunction with the core silica detection principles, this technology is also aligned to provide a monitoring methodology that puts data into the users hands without the need for complex set-up, calibration or usage routines or any requirement for specialist interpretation of data. The real-time data collected is used to display instantaneous, on-device values that relate directly to the changing silica levels within the working environment. This can be used to monitor results locally (on-device), or if required, to trigger a series of alarms which instantly warn about unsafe levels of silica dust based on programmable set-points.

During the collection of particle data, the device can be set to monitor at various logging rates to give more or less detailed overviews of the working period (as frequent as every second), depending on the overall requirements. Measurements can also be monitored against multiple averaging periods to give an overview for short term exposure limits as well as WEL related operating levels – all of which takes place simulatenously, and in real-time giving a live picture of the current silica levels against previously recorded measurements.

In addition, the data collected can be pushed remotely to a central application which is used to monitor and plot data sets for analysis purposes. Data-driven decisions can be made using the real-time overview of local environments or working practices, which can act to keep workers from being exposed to unusually high levels of silica or identify processes that are contributing to generation and release of occupational dust.

Collected data can also be stored, graphed and compared against a timeline of events to demonstrate the overall particulate picture for a given working environment, and when continuously monitored, acts to track and support critical control management, validate the effectiveness of measures and highlight exposure trends.

This move to real-time silica monitoring has the potential to fundamentally change every aspect of how the industry, regulators and workers think about, regulate and respond to the presence of this killer particulate in any workplace as the next section discusses.

The benefits and possibilities of real-time silica monitoring

RTPM for general dust is beginning to be understood as a key methodology that can bring significant benefits to industry as a rapid analytical tool for understanding, monitoring and mitigating respiratory risk[13].

The benefits are potentially wide-ranging as the International Council for Mining and Metals report entitled “Considerations for the adoption of real-time particulate monitoring” discusses at length. Whilst the report is aimed principally at mining operations, the conclusions can be applied across a range of hazardous industries where particulates present a present a risk. The report lists the following eight principal benefits:

1. Rapid and timely airborne particulate data that can be used to protect miners.

2. Effective tool in CCM (Critical Control Management) used to validate the effectiveness of critical controls, mitigating airborne particulates where exposures have the potential for high-probability fatal outcomes.

3. Ability to identify and pin-point specific particulate emission sources.

[13] ICMM report on real-time particulate monitoring, 2022.

4. Identification of specific activities within job tasks where overexposures occur, informing mitigation and control strategies.

5. Rapidly identify uncontrolled or unexpected critical releases of hazardous particulates.

6. Early warning of out-of-specification operations, enabling preventive maintenance before catastrophic failure of equipment.

7. Latest RTPM instruments are becoming small enough for use in personal dust sampling.

8. Validation of environmental and occupational dust controls.

However the report also details the many problems with RTPM and the instruments currently available on the market, not least of which is the fact that “current RTPM technology does not support speciation of particulates and no RTPM instruments cover the entire size range germane to respiratory hazards (< 0.5µm - 100µm).” In the case of silica, then the instruments will not identify and distinguish it from other usually less-harmful particulates and therefore will not be able to accurately assess and communicate the actual level of risk to workers and management.

This issue alone is enough to undermine many of the benefits listed above and the ICMM report goes on to point out other issues around RTPM technologies currently available including the challenging nature of field-calibration, the high cost of purchase and maintenance of the equipment, the high level of specialist knowledge required to operate the units and the impractical nature of many of the products (size, weight, complexity, fragility etc.).

As we have seen OP-ORT has the potential to solve many of the issues discussed by the ICMM report. First and foremost it detects and distinguishes silica, and can track changing levels and concentrations over time – and it can be presented in a field-ready product that is robust, low-maintenance, affordable and easy to use. The benefits for industry, workers, regulators, and society in general, of this advancement in technology can be broadly divided into four main categories:

1. Safety

2. Control

3. Efficiency and cost reduction

4. Collaboration and culture

Safety

The most obvious and immediate benefit is in improving safety for those potentially exposed to silica in the workplace. By providing warnings in real-time either through local alarms or via networked systems, OP-ORT provides an immediate, actionable incentive to respond instantly to the danger, in exactly the same way that the majority of workers are trained and willing to respond to a fire alarm or a gas detection system. When allied with clear HR controls and procedures, and linked directly to regulated exposure levels for silica, backed-up by training and high levels of awareness around the potential dangers, OP-ORT instruments will be able to drive a change in safety standards and ultimately the whole outlook in relation to particulates in the workplace.

It is significant that deaths and harm from toxic gasses in the workplace have been reduced almost to zero in advanced economies in part due to the use of real-time detection methods and alarms, and by shifting the view of particulates from something that may not be especially dangerous or something that may only affect an individual decades into the future, to something that is an immediate and present threat, OP-ORT can not only improve safety through instant alarming, but it can also help to shift the safety culture across industry and society around particulates.

Intelligent placement and usage of the instruments can also widen the safety net offered by monitoring technology by assessing in real-time exposure levels outside of front-line workers, for example in support administration buildings, vehicle cabs and at the boundaries of industrial sites.

Control

The move to real-time silica monitoring through the adoption of OP-ORT has the potential to allow businesses and individuals to develop better and more responsive critical control structures in the operating environments where RCS is generated. The ICMM report considers a number of ways in which real-time and historical data allows businesses to better understand what is happening in their facility, and to make the appropriate engineered responses to RCS, as well as improving HR policies and developing process changes. Examples of improved information and control outcomes include:

- facilitating smart dust suppression, extraction, ventilation and control measures;
- identification of high-risk tasks within the work-flow;
- improved field-based evidence to support best practices.

- supporting the selection and usage of the right type of RPE;
- and optimising process methods, and equipment to reduce exposure.

In addition to the positive outcomes associated with real-time silica monitoring, the ease-of-use and low maintenance requirements of OP-ORT instruments allow businesses to bring management and reporting of the exposure profile in their facility back in-house or as part of their general engineering or health and safety team, rather than engaging outside consultants or needing a dedicated department or team of specialist employees. OP-ORT instruments require no set-up or calibration, begin monitoring within a few seconds of start-up, and require no specialist equipment or skills to maintain. Maintenance requirements are only a few minutes each month and data is easily captured and represented through accessible software, giving businesses the information they need to minimise harm and build a hierarchy of control that is genuinely responsive to changing conditions and circumstances without disruption to their core activity.

One complication to the move to a more easily manageable RCS monitoring profile is the procedures laid down by regulation. Real-time silica detection (and in fact real-time particulate detection of any kind) in the workplace is not currently supported by regulatory structures anywhere in the world, and therefore the current methodology, which in most territories is still based around gravimetric sampling, will still need to be implemented. It is likely to be some considerable time before legislation and regulations catch-up with the technological developments and expanded control options that OP-ORT offer, however there is still a strong case for the deployment alongside the current methodology even before regulations change.

Firstly for businesses carrying out regular surveys in order to build a picture of the RCS generation and exposure profile within their facility and to report to regulatory bodies, the use of OP-ORT alongside gravimetric sampling has the potential to radically improve the outcomes of those surveys. Through the provision of instantly accessible real-time data during or even prior to the survey, a framework that maximises the impact and accuracy of the survey can be created improving the survey outcomes and/or reducing the resource requirements.

For those businesses that recognise the limitations of the current methodologies and who are working towards a zero harm workplace through the elimination of exposure to hazardous airborne particulates then deploying OP-ORT will be viewed as a necessary step on the grounds of safety alone. However, in many instances there will not need to be a choice made between safety and cost in the deployment of OP-ORT products as the technology can both reduce cost and improve process efficiency in many businesses in addition to its safety and control benefits.

Cost and efficiency

Adoption of real-time silica monitoring using open-path ORT can reduce costs and improve efficiency in process industries in a number of ways depending on the operational particulars of a facility and the business strategy. Deploying the technology in a proactive and strategic way can lead to the following potential savings:

1. Immediate identification of process breakdowns or inefficiency allowing the business to make corrections, repairs and improvements as they are required, and preventing catastrophic breakdown from unidentified issues that are allowed to develop unchecked.

2. Continuous validation of RCS control and removal mechanisms allows smart systems to be developed and deployed. Dust suppression, ventilation and extraction systems are expensive to operate and are often utilised in combination with each other or with other harm mitigation methodologies, so optimising their performance using real-time data is critical not only in making them more effective but also in facilitating the most efficient utilisation.

3. Further to this, capital expenditure decisions related to hazardous particulate control and elimination can be based on real-time and continuous evaluation of their effectiveness and with a greater understanding of the developing exposure profile within the business.

4. For those businesses handling and processing valuable material real-time evaluation of process breakdown can minimise material losses, and through continuous end-to-end monitoring process design can be improved to ensure long-term efficiency.

5. Purchasing decisions and protocols and policies around the use of RPE can also be improved through the availability of comprehensive information on potential exposures to RCS throughout a facility.

6. Reducing the frequency and length of surveys designed to meet regulatory requirements or to inform the hygiene programme developed to eliminate risk can deliver considerable cost savings to businesses, both through reduced third-party costs and also reduced disruption to business processes.

7. The ICMM report estimates that the typical maintenance costs of products currently on the market as being around $10,000 pa with the specialist skills required to manage and discern data costing around $150,000 - $200,000 per annum. OP-ORT devices can remove most of these costs.

8. Improvements in critical control methodologies and the resultant reduction in exposure of workers can lead to better health outcomes, reduced sick days and long-term absences as well as reduced health scheme and insurance premiums.

It is now firmly established that long-term exposure to silica dust, or even short-term exposure at high levels, has the potential to result in negative health outcomes and even death. The on-going viability of any business that exposes its workforce to hazardous particulates could be affected in the near future if that business fails to develop reasonable responses to the threat. The issues around the effectiveness, costs and viability of existing technologies to properly monitor and mitigate the harm being done have made it difficult even for organisations with the very best intentions to develop comprehensive management and control strategies and procedures. OP-ORT changes that equation in a radical way.

Collaboration and culture

As discussed in the introduction to this paper, there has been a constant tension over the years between the desire to protect those exposed to RCS in the workplace, and the technological viability of being able to do so, and a part of that on-going debate and discussion is inevitably focussed on the cost and resource requirements that providing effective monitoring and protection would require. Tensions between governments, regulators, industry groups, unions and workers themselves have often resulted in defensive positions being taken and little progress being made in actually reducing the harm being caused.

In the UK, the HSE has come under heavy criticism for its perceived failure to protect workers, with Professor Rory O'Neill of the Occupational and Environmental Health and Safety Research Group (OEHSRG) stating in 2014 that "The HSE says monitoring technology isn't good enough yet to measure low levels of silica dust, so we must stick with the same deadly, higher but measurable standard. It is wrong on both counts".

In response, the HSE insisted that the technology was not available to reasonably and practicably enforce lower standards stating "The advice HSE has received indicates that it is not practical or achievable to consistently and reliably measure real workplace samples of respirable crystalline silica to significantly lower levels. This is because the technical samplers currently used suffer from interference and poor precision at these low measurement masses. Measurements below the current WEL would require complex sampling and analysis processes which have not been validated."

Whilst the exposure limits in the US are lower than the UK, the regulating body OSHA has frequently been accused of failing to enforce these lower standards and thereby failing to protect workers from harm. Debate has been intense over the costs of implementing these lower standards with The Construction Industry Safety Coalition (CISC) claiming that the reduced exposure limits would cost the construction industry alone over $4 to $5 billion in lost jobs and a further $1 billion in protective equipment.

In Australia, as recently as January 2021, the Australian Workers Union has described the standards and enforcement exposure to silica dust as 'shameful' and has called for tough penalties for those businesses failing to comply with reduced exposure limits. WorkSafe Australia has reduced the exposure limits further since then and Australia now has the lowest exposure limits in the world with WorkSafe now focusing on enforcement and bringing charges against a number of companies for failure to comply.

The arrival of OP-ORT for real-time silica detection offers the opportunity for a reset in the debate around legislative limits and the most practicable methodology for reducing harm and controlling the impact on a business's operating efficiency. OP-ORT can accurately detect the presence of RCS and can distinguish it in dust mixtures as well as being able to track changing concentrations over time. Importantly ORT has the potential to accurately detect quantities of silica dust at regulated levels and lower, thereby ending the argument over whether technology is capable of supporting regulated limits. The technology opens up the possibility not only of being able to adequately support existing limits but of allowing scientists and researchers to reliably establish the long-term exposure levels that lead to harm and for legislation to then follow on from those findings.

On the other side of the debate, OP-ORT is a low-cost solution, with minimal additional maintenance and ownership costs and can be implemented without specialist knowledge and skills. It carries with it the potential for significant cost-savings in many business operations and provides brands with long-term protection against litigation and reputational damage associated with the harm caused by silica dust. Its arrival changes the discussion around the cost and resources required to protect workers from silica dust.

It should be hoped that a collaborative approach can be established between regulators, businesses and workers groups that can develop a common-sense introduction of the technology across all industries where exposure to RCS is an issue, and establish frameworks of best practice and regulatory changes that realise its potential to both reduce harm and improve relations between these groups and to improve working cultures within industries and individual businesses.

A note on mg/m^3 and legislative limits

Exposure limits for hazardous particulates including silica are generally expressed in mg/m^3 for an average shift length, working day or collection timeframe (typically eight to 10 hours). This is a measure of density, and relates to the total weight of a collected particulate sample in a defined volume of air.

The adoption of this unit of measurement was driven by two factors. That this was the outcome from the best available technology for particulate detection at the time (gravimetric sampling) and by the assumption that the weight of inhaled particulate was a good measure of its potential to do harm.

Both of these assumptions are now redundant. It has been clearly demonstrated that smaller particulates generally pose a much greater threat to human health than larger particulate as, according to the US Environmental Protection Agency “they can get deep into your lungs, and some may even get into your bloodstream.” It follows, therefore, that the weight or mass of particle matter is not the only factor in determining the danger posed by particulates and that the total cross-section of particle sizes present within working environments must be taken into account, and not just a pre-defined size range created using cyclones and filters.

OP-ORT measures every particle in a given sample and is also capable of accurately sizing particles. Whilst it can output results in mg/m^3 through a conversion algorithm its actual outcome is expressed in particles per litre. This opens up the intriguing possibility of developing a more accurate report that is closely aligned with a-silica particles potential to cause harm. Limits could be developed and expressed in particles per litre, factoring in the size distribution of the RCS sample, and culminating in legislation that properly reflects its intention – to protect respiratory health in humans in the most accurate way possible.

Glossary of acronyms

AIOH	Australian Institute of Occupational Hygienists
BOHS	British Occupational Hygiene Society
CCM	Critical Control Management
CFMMEU	Construction Forestry Maritime Mining Energy Union
COPD	Chronic Obstructive Pulmonary Disease
COSHH	Control of Substances Hazardous to Health
CWP	Coal Workers' Pneumoconiosis
DoF	Direct on Filter
EDS	Energy-Dispersive Spectroscopy
EPA	Environmental Protection Agency
ESLI	End of Service Life
FTIR	Fourier Transform Infra-Red Spectroscopy
HRCT	High-Resolution Computed Tomography
HSE	Health and Safety Executive

HSR	Health and Safety Representatives
IBA	Ion Beam Analysis
IR	Infrared Spectroscopy
IROC	Integrated Remote Operations Centre
ISO	International Organisation for Standardization
JSOH	Japanese Society of Occupational Health
LIBS	Laser-Induced Breakdown Spectroscopy
MOUDI	Micro Orifice Uniform Deposit Impactor
NIOSH	National Institute for Occupational Safety & Health
NMAM	NIOSH Manual of Analytical Methods
NSW	New South Wales
OPC	Optical Particle Counting
OREP	Occupational Risk Exposure Profile
ORT	Optical Refraction Technology
OSHA	Occupational Safety and Health Administration

PEL	Permissible Exposure Limits
PFR	British Pneumoconiosis Field Research
PPE	Personal Protective Equipment
QCL	Quantum Cascade Laser
RACP	Royal Australasian College of Physicians
RCS	Respirable Crystalline Silica
ROS	Reactive Oxygen Species
RPE	Respiratory Protective Equipment
RTPM	Real-Time Particulate Monitoring
SCADA	Supervisory Control and Data Acquisition
SCOEL	Scientific Committee on Occupational Exposure Limits
SEG	Similar Exposure Groups
SiO_2	Silicon dioxide
SiOH	Silanol
TOEM	Tapered Element Oscillating Microbalances

TWA	Time-Weighted Average
UK	United Kingdom
USA	United States of America
VIS	Visible Absorption Spectrophotometry
VOD	Ventilation on Demand

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